

3-D LITHOGRAPHY AND METAL SURFACE MICROMACHINING FOR RF AND MICROWAVE MEMS

Jun-Bo Yoon, Byeong-Il Kim, Yun-Seok Choi, and Euisik Yoon

*Department of Electrical Engineering and Computer Science
Korea Advanced Institute of Science and Technology (KAIST)*

373-1 Kusong-dong, Yusong-gu, Taejeon 305-701, Korea, Email: jbyoon@ee.kaist.ac.kr

ABSTRACT

A new metal surface micromachining technology utilizing 3-D lithography, electroplating, and mechanical polishing has been developed to fabricate arbitrary 3-D metal microstructures as post-IC processes at low temperature below 120°C. Using this technology, various highly-suspended 3-D microstructures have been successfully demonstrated for RF and microwave MEMS applications. We have fabricated spiral inductors suspended 100 μm over the substrate, coplanar waveguides suspended 50 μm over the substrate, and complicated micro-coaxial lines which have 50 μm -suspended center signal lines surrounded by ground shields of 100 μm in height.

I. INTRODUCTION

As wireless telecommunication is gaining great importance in emerging commercial markets, there have been strong demands for high-performance, monolithic, low-cost passive components in RF and microwave applications. This leads that the MEMS technology has been also spotlighted in the fields of RF and microwave applications as the MEMS technology can give us an alternative technological option providing advantages of remarkable reduction in substrate coupling and ohmic loss. Various bulk and surface micromachining technologies have been investigated so far to achieve more than an order of magnitude improvement in size, cost, and performance in the RF/microwave applications [1]–[3].

From this perspective, metal surface micromachining has been investigated using X-ray LIGA [4] and LIGA-like UV technologies [5]–[8] during the last decade, as a technique to build microstructures on the top of substrate. It consists of fabrication of molds followed by electroplating. As a mold for electroplating-guide, various materials have been investigated, such as electron-beam-sensitive PMMA [4], UV-sensitive polyimide [5], conventional positive thick photoresist [6], [7], and epoxy-based negative thick photoresist [8]. Among these, the conventional positive thick photoresist is the most suitable one to use in terms of process simplicity, process time, and compatibility. Instead of multi-stacking 2-D molds and metal to fabricate 3-D microstructures [9]–[11], there has been an approach to realize 3-D photoresist molds directly in order to obtain 3-D metal microstructures at once [12]. This method has been applied to fabricate solenoid inductors [13]–[15]. Instead of

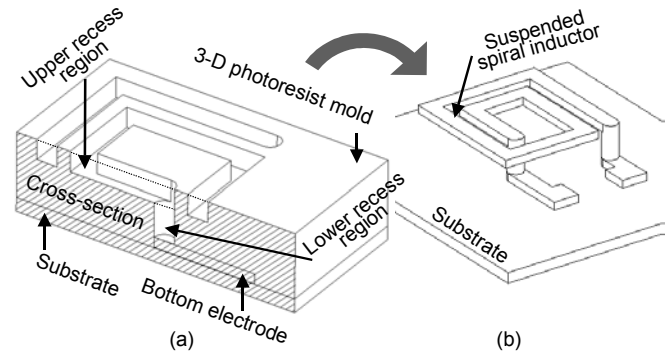


Fig. 1. Brief schematic presentation of the proposed 3-D metal surface micromachining technology: (a) 3-D photoresist mold for a suspended spiral inductor and (b) fabricated suspended spiral inductor.

polymer-based molds, a sacrificial metal mold has also been reported [16] and applied to fabricate inductors [17], [18] and transformers [19].

In this paper, we report a robust, versatile, and manufacturable metal surface micromachining technology based on the multi-exposure and single development (MESD) method reported previously [12]. In this work, we have developed a new fabrication process to improve the MESD method, so that we can overcome the major drawback of the previous approach (size limit in the suspended microstructure), which makes its application fields very limited, and we can build arbitrary shapes of highly-suspended thick-metal microstructures.

II. FABRICATION

The fabrication process is very simple: first, we make a 3-D photoresist mold having arbitrarily-shaped upper recess regions as shown in Fig. 1; second, fill both lower and upper recess regions with metal; and finally remove the photoresist molds. Fig. 1 also shows the cross-sectional area which is used to explain the process flow shown in Fig. 2. In Fig. 2, the process starts with a substrate on which the bottom seed metal (Ti/Cu) is deposited. The bottom Cu electrode is then formed by the conventional lithography with a thick photoresist followed by electroplating. After removing the photoresist, another thick photoresist (usually over 50 μm in thickness) is spun on the wafer, as shown in Fig. 2a. After the two-step UV exposure with two different photomasks and exposure times, single-step development reveals the 3-D

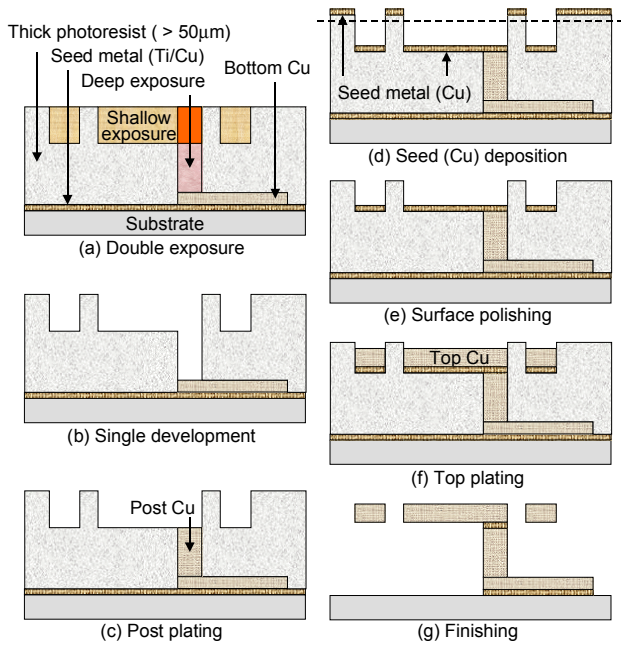


Fig. 2. Fabrication process flow of the proposed method.

photoresist mold as shown in Fig. 2b. The typical MESD process conditions can be found in [13].

Once the 3-D photoresist mold is fabricated, the lower recess region is filled with the electroplated metal to form the posts in Fig. 2c. The Cu electroplating solution used in this work has been reported in [13]. Since the post electroplating is done filling upward from the bottom of the lower recess region, we can obtain fully-filled, robust posts. After the post electroplating, the surface is covered by another seed metal (Cu) as shown in Fig. 2d. To make it sure that the next electroplating occurs only in the upper recess regions, as shown in Fig. 2f, the topmost seed metal is removed at the step in Fig. 2e. The dashed line shown in Fig. 2d indicates the boundary to which the mechanical polishing is done. We successfully used mechanical polishing in removing the topmost seed metal.

Next, another electroplating is performed to fill the upper recess regions with metal as shown in Fig. 2f. Since all 2nd seed metal in the upper recess regions are electrically connected to the bottom seed metal through the metal posts, all the upper recess regions are simultaneously filled during the electroplating. This makes it possible to obtain longer and arbitrarily-shaped suspended structures. Finally, the sacrificial 3-D photoresist mold is removed in acetone and the bottom seed metal is etched for electrical isolation between devices. The final suspended microstructure is shown in Fig. 1b and Fig. 2g.

III. RESULTS AND DISCUSSION

Fig. 3 shows the SEM photographs of the 3-D photoresist mold fabricated by the new MESD method. The shallow-exposure depth has been controlled by exposure time

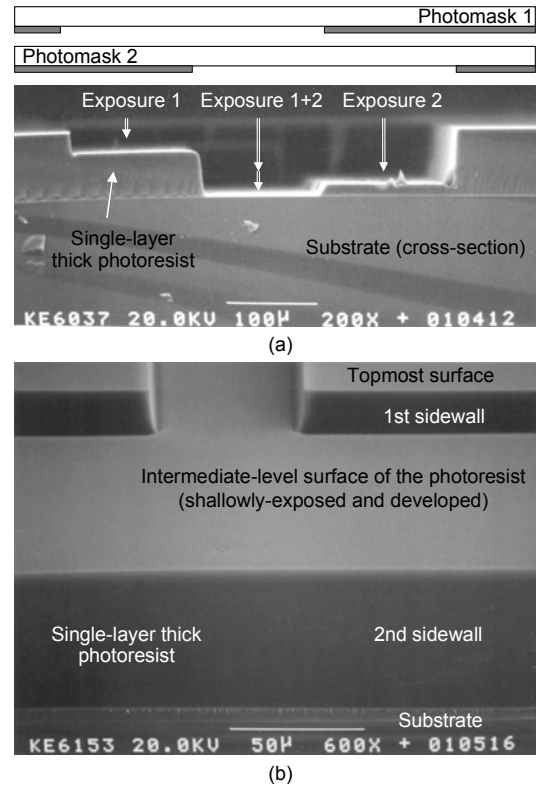


Fig. 3. SEM photographs of the 3-D photoresist mold fabricated by the proposed MESD method: (a) cross-sectional view showing dual intermediate levels within a single-layer photoresist and (b) perspective view showing very smooth intermediate-level surface of the single-layer photoresist.

utilizing the characteristics that the development is held up (saturated) at a certain but well-predictable depth in the photoresist when the exposure is insufficient [13]. Although we have utilized only single intermediate level within the photoresist as shown in Fig. 2b, Fig. 3a shows that we can obtain dual intermediate levels within the photoresist by utilizing the overlapped exposure. The relevant photomasks has been shown in the figure as well. This may increase the 3-D versatility of this technology for obtaining more complicated microstructures. As can be seen in Fig. 3b, the surface of the intermediate level within the single-layer photoresist was very smooth.

The polished surface of the topmost photoresist has to be well controlled. In Fig. 4, the top surface of the photoresist has remained in a good shape after polishing the 2nd seed metal layer. No residue of the 2nd seed metal has been observed, no surface photoresist structure has been damaged, and the 2nd seed metal on the bottom of the upper recess regions has remained well.

Fig. 5 demonstrates the fabricated solenoid structure with very long bridges, which clearly could not be made by the original MESD process [13]. Also, the robust post structure can be made by the reason as described in the corresponding process step. Note that, owing to the excellent planarization capability of the photoresist mold, we cannot observe any marks of the bottom electrodes imprinted onto the upper

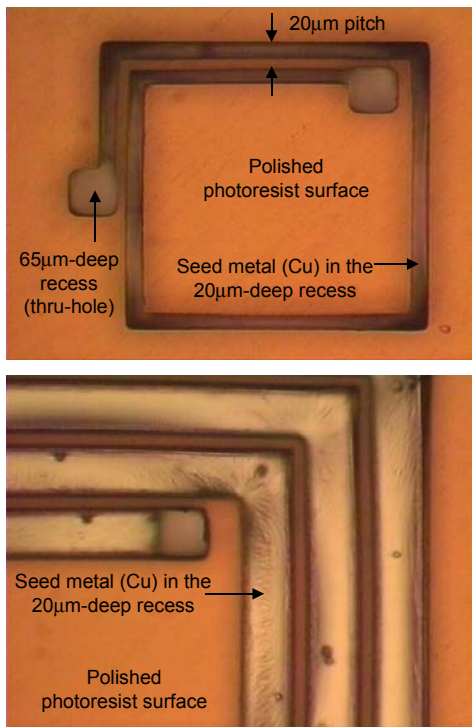


Fig. 4. Optical photograph of the polished photoresist surface taken after the topmost 2nd seed metal has been removed by the mechanical polishing.

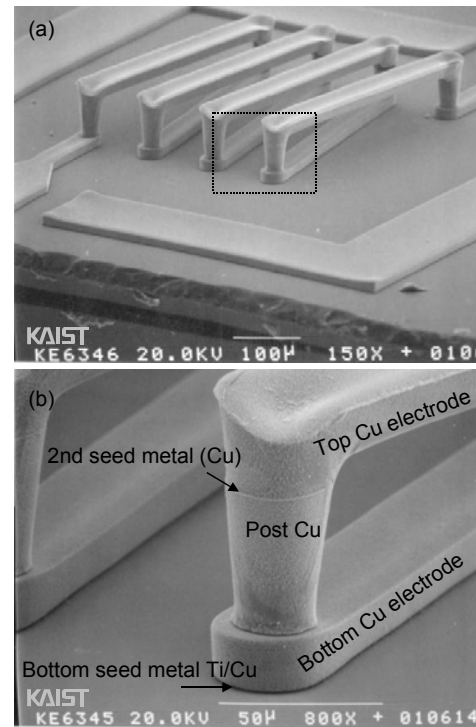


Fig. 5. SEM microphotographs of the fabricated solenoid structures: (a) bird's view, (b) magnified view of the post structure.

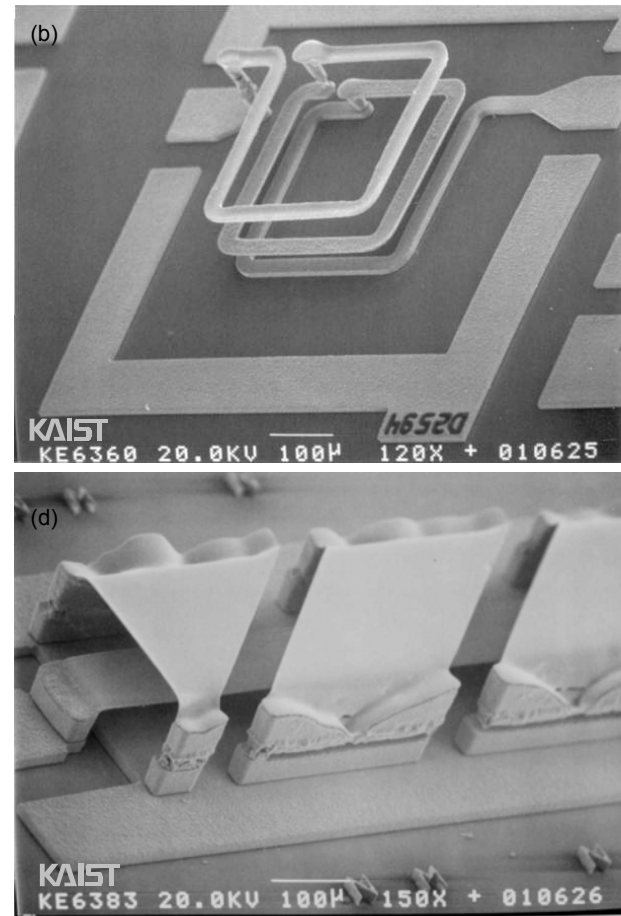
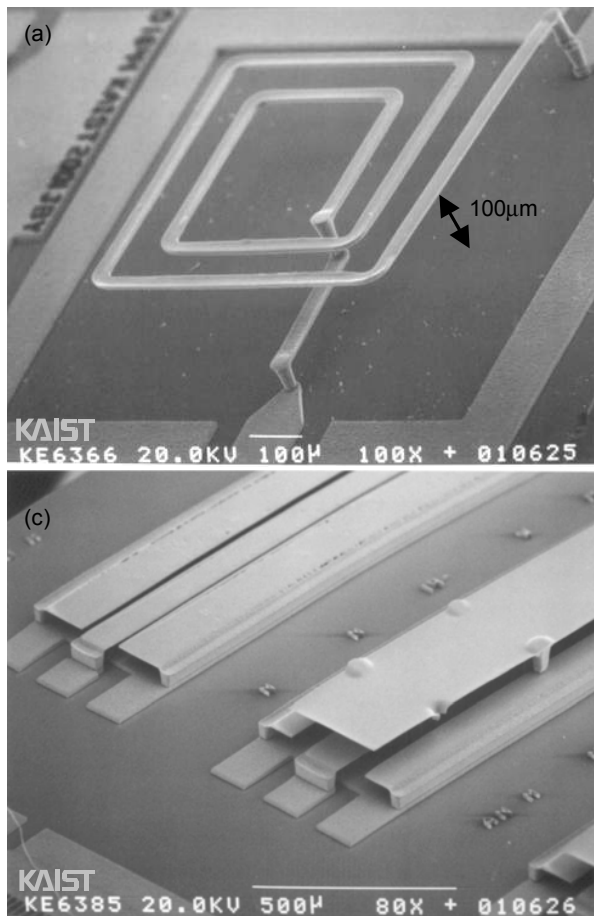


Fig. 6. SEM photographs of the fabricated 3-D microstructures: (a) a spiral inductor suspended by 100μm over the substrate supported on two signal posts, (b) a vertical solenoid inductor, (c) coplanar transmission lines, and (d) a micro-coaxial transmission line with inclined shields.

suspended electrodes, which also was not the case in [16].

Fig. 6 shows the SEM photographs of the various inductors and transmission lines fabricated by using the proposed technology. From all the structures in Fig. 6, one can see that they have been easily shaped in many variations and suspended flat, due to the excellent planarization capability of the sacrificial photoresist mold. The flat suspended lines also indicate no internal stress gradient residing in the electroplated metal structures. In Fig. 6, we have demonstrated spiral inductors suspended 100 μm over the substrate, coplanar waveguides suspended 50 μm over the substrate, and complicated micro-coaxial lines which have 50 μm -suspended center signal lines surrounded by inclined ground shields of 100 μm in height. The RF performance of the suspended inductors fabricated by this technology has been submitted as a separate report [20]. All the multi-level microstructures in Fig. 6a through Fig. 6d have been made by a repetition of the fundamental process shown in Fig. 2. This demonstrates that our technology is versatile to construct multi-level, fairly-complicated microstructures, such as the 3-D micro-coaxial line in Fig. 6d.

We have obtained the whole process yield of over 90% among 4,000 inductors fabricated on a 4-inch wafer in our university fabrication facility, which makes the technology fairly manufacturable. All the process temperature has been below 120°C, which makes it possible to integrate our surface-micromachined passive components onto the wafer that has finished the IC process.

IV. CONCLUSIONS

The new thick-metal surface micromachining technology has been developed with strong emphasis on structural robustness, versatility and reliability, and CMOS-compatibility and process manufacturability. This new process has several advantages: (1) thick sacrificial layers (>100 μm) can be easily fabricated and removed; (2) highly-suspended microstructures can be fabricated uniformly and reproducibly; (3) flat top-layer microstructures can be fabricated; (4) the post can be constructed robust. This technology is believed to serve as a versatile, robust, and manufacturable tool to implement various 3-D microstructures as well as high-performance RF and Microwave MEMS components.

ACKNOWLEDGMENTS

The authors would like to thank Il-Joo Cho and Byoung-Gyun Kim for taking SEM pictures. This work has been supported by National Research Laboratory grant from Ministry of Science and Technology in Korea.

REFERENCES

- [1] C. T.-C. Nguyen, L. P. B. Katehi, and G. M. Rebeiz, "Micromachined devices for wireless communications," *Proceedings of The IEEE*, vol. 86, pp. 1756-1768, Aug. 1998.
- [2] J. J. Yao, "RF MEMS from a device perspective," *J. Micromech. Microeng.* vol. 10, pp. R9-R38, Dec. 2000.
- [3] R. J. Richards and H. J. De Los Santos, "MEMS for RF/microwave wireless applications: the next wave," *Microwave J.*, vol. 44, pp. 20-41, Mar. 2001.
- [4] H. Guckel, "High-aspect-ratio micromachining via deep X-ray lithography," *Proceedings of The IEEE*, vol. 86, pp. 1586-1593, Aug. 1998.
- [5] A. B. Frazier and M. G. Allen, "Metallic microstructures fabricated using photosensitive polyimide electroplating molds," *IEEE J. MEMS*, vol. 2, pp. 87-94, June 1993.
- [6] G. Engelmann, O. Ehrmann, J. Simon, and H. Reichl, "Fabrication of high depth-to-width aspect ratio microstructures," in *IEEE Proc. MEMS*, Feb. 1992, pp. 93-98.
- [7] B. Loechel, A. Maciossek, and M. Rothe, "Application of ultraviolet depth lithography for surface micromachining," *J. Vac. Sci. Technol. B*, vol. 13, pp. 2934-2939 Nov/Dec. 1995.
- [8] K. Y. Lee, N. LaBianca, S. A. Rishton, S. Zolgharnain, J. D. Gelorme, J. Shaw, and T. H.-P. Chang, "Micromachining applications of a high resolution ultrathick photoresist," *J. Vac. Sci. Technol. B*, vol. 13, pp. 3012-3016 Nov/Dec. 1995.
- [9] Y.-J. Kim and M. G. Allen, "Surface micromachined solenoid inductors for high frequency applications," *IEEE Trans. Comp. Packag. and Manufact. Technol.*, pt. C, vol. 21, pp. 26-33, Jan. 1998.
- [10] J. Y. Park and M. G. Allen, "Micromachined high Q inductors for high frequency applications," in *Proc. SPIE*, vol. 3514, Sep. 1998, pp. 218-228.
- [11] R. C. Alford, R. E. Stengel, D. H. Weisman, and G. W. Marlin, "Method of forming a three-dimensional integrated inductor," *US Patent # 6,008,102*, Dec. 1999.
- [12] J.-B. Yoon, J.-D. Lee, C.-H. Han, E. Yoon, and C.-K. Kim, "Multilevel microstructure fabrication using single-step 3D photolithography and single-step electroplating," in *Proc. SPIE*, vol. 3512, Sep. 1998, pp. 358-366.
- [13] J.-B. Yoon, C.-H. Han, E. Yoon, and C.-K. Kim, "Monolithic fabrication of electroplated solenoid inductors using three-dimensional photolithography of a thick photoresist," *Jpn. J. Appl. Phys.*, vol. 37, pt. 1, no. 12B, pp. 7081-7085, Dec. 1998.
- [14] J.-B. Yoon, B.-K. Kim, C.-H. Han, E. Yoon, K. Lee, and C.-K. Kim, "High-performance electroplated solenoid-type integrated inductor (SI²) for RF applications using simple 3D surface micromachining technology," in *IEEE Int. Electron Devices Meet. Tech. Dig.*, Dec. 1998, pp. 544-547.
- [15] J.-B. Yoon, B.-K. Kim, C.-H. Han, E. Yoon, and C.-K. Kim, "Surface micromachined solenoid on-Si and on-glass inductors for RF applications," *IEEE Electron Device Lett.*, vol. 20, pp. 487-489, Sep. 1999.
- [16] J.-B. Yoon, C.-H. Han, E. Yoon, and C.-K. Kim, "Monolithic integration of 3-D electroplated microstructures of unlimited number of levels using planarization with a sacrificial metallic mold (PSMM)," in *IEEE Int. MEMS Conf. Tech. Dig.*, Jan. 1999, pp. 624-629.
- [17] J.-B. Yoon, C.-H. Han, E. Yoon, and C.-K. Kim, "High-performance three-dimensional on-chip inductors fabricated by novel micromachining technology for RF MMIC," in *IEEE MTT-S Int. Microwave Symp. Dig.*, June 1999, pp. 1523-1526.
- [18] J.-B. Yoon, C.-H. Han, E. Yoon, and C.-K. Kim, "Monolithic high- Q overhang inductors fabricated on silicon and glass substrates," in *IEEE Int. Electron Devices Meet. Tech. Dig.*, Dec. 1999, pp. 753-756.
- [19] Y.-S. Choi, J.-B. Yoon, B.-I. Kim, E. Yoon, and C.-H. Han, "Fabrication of a solenoid-type microwave transformer," in *Transducers '01*, June 2001, pp. 1564-1567.
- [20] J.-B. Yoon, Y.-S. Choi, B.-I. Kim, Y. Eo, and E. Yoon, "CMOS-compatible, surface micromachined, suspended spiral inductors on standard silicon for multi-GHz silicon RF IC's," a paper has been submitted to *IEEE Electron Device Letters*.